

Analysis of a Diesel-Electric Hybrid Urban Bus System

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ABSTRACT

A hybrid bus powered by a diesel engine and a battery pack has been analyzed over an idealized bus-driving cycle in Chicago. Three hybrid configurations, two parallel and one series, have been evaluated. The results indicate that the fuel economy of a hybrid bus, taking into account the regenerative braking, is comparable with that of a conventional diesel bus. Life-cycle costs are slightly higher because of the added weight and cost of the battery.

INTRODUCTION

Various forms of hybrid power systems are being considered for reducing emissions and substituting fuels in transportation applications (such as cars and buses). Hybrids are considered primarily because all-electric power systems do not provide adequate range and are not yet cost-effective. Urban buses are typically powered by diesel engines, which are subjected to considerable load and speed transients. Such transients can adversely affect fuel economy and increase smoke, particulate, and other emissions. The purpose of the present study is to evaluate several hybrid configurations consisting of a diesel engine and a battery pack in terms of capital and operating cost characteristics relative to the baseline diesel bus.

HYBRID CONFIGURATIONS

Three hybrid configurations, two parallel (Configurations A and B) and one series (Configuration C), have been considered in the present study.

Configuration A (see Fig. 1.1) is a parallel hybrid with the so-called dual-peaking power-management strategy [1]. In this strategy, the battery provides the primary source of power as long as its state of charge is above a predetermined value, SOC_T . In this mode of operation, the diesel engine is used as the peaking device whenever the power requirement of the

vehicle exceeds the battery power capability. After the battery energy is depleted such that its percent depth of discharge (DOD) reaches $DOD_T (= 100 - SOC_T)$, the diesel engine takes over and acts as the primary power source. The battery then provides the necessary peaking power upon demand. In this mode of operation, the diesel engine also recharges the battery whenever it has power to spare to maintain the state of charge of the battery at or above SOC_T .

Configuration B is similar to Configuration A (see Fig. 1.1), except that the battery in this case always acts as the primary power source. The diesel engine provides the necessary peaking power and continuously recharges the battery to maintain it above a desired minimum level of charge.

Configuration C, shown in Fig. 1.2, is a series hybrid arrangement with the battery providing the primary power at all times. An engine/generator capable of maintaining the battery above a desired minimum charge level also provides the necessary peaking power. The electric energy from the generator is used directly to energize the motor during peak power demand.

In all of the above configurations, it is assumed that neither the battery nor the diesel engine alone is capable of supplying the entire power demand of the vehicle; when one provides the primary power, the other must supply the peaking power upon demand. For this reason, it is assumed that the diesel engine never shuts down; it idles when no power is needed.

Since most state-of-the-art electric drivelines do not require a multispeed transmission [2], no transmission is assumed for the electric drivelines in all of the configurations considered.

COMPUTER SIMULATION

MARVEL, an interactive microcomputer software package [1], was modified and used in the present study. MARVEL was developed for analyzing battery/heat

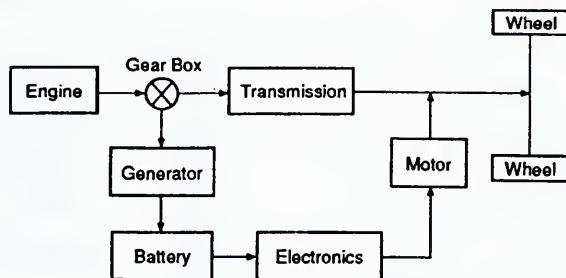


Fig. 1.1 Block Diagram of a Parallel Hybrid Vehicle

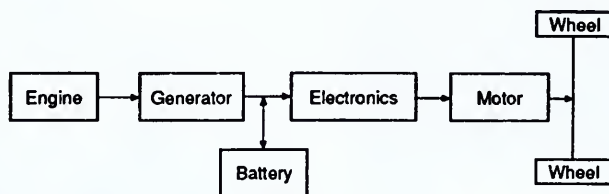


Fig. 1.2 Block Diagram of a Series Hybrid Vehicle

engine/hybrid vehicle systems. It enables analyses of least life-cycle costs that identify the optimal combination of battery and heat engine characteristics for different vehicle types and missions. An engine performance map based on a turbocharged, four-cylinder, indirect-injection diesel engine was simulated and included in MARVEL. Another modification made to the software package was the inclusion of the option to simulate regenerative braking.

Input data to MARVEL were generated on the basis of assumptions listed in Tables 1 through 3 for the vehicle, engine, and battery, respectively. The characteristics of the vehicle correspond to a typical bus operated by the Chicago Transit Authority (CTA). The battery characteristics are based on the mid-term goals of the U.S. Advanced Battery Consortium (USABC). The battery is assumed to be fully charged each morning before the commencement of the daily mission. An average efficiency of 75% is assumed to be constant over the life of the battery. Economic assumptions used in the analysis are listed in Table 4.

An idealized driving cycle, shown in Fig. 2, was developed for the study on the basis of a typical CTA bus route. Table 5 lists the pertinent data for the driving cycle. The vehicle is assumed to be driven repeatedly over the driving cycle for a total of 260 km each day of the year.

RESULTS

The peak power requirement for the bus negotiating the assumed driving cycle is calculated to be 11.1 W/kg, with an average energy requirement of 0.126 W·h/km·kg. For each configuration, MARVEL searches for the combination of diesel engine and battery characteristics that leads to the lowest life-cycle cost for the intended mission.

Results of the calculations are presented in Table 6. For comparison, the performance of a typical diesel bus is also included in the table. The annual energy costs (including both diesel fuel and electricity) of the hybrid configurations reflect the assumption of a 40% overall efficiency of regenerative braking. Because of the stop-and-go nature of the driving cycle, the assumption is considered to be conservative [3].

The vehicle cost for Configuration C, the series hybrid, is lower mainly because it does not require a transmission. This saving in vehicle cost more than offsets the slightly higher energy cost, and gives the series hybrid a slight edge in the life-cycle cost. The life-cycle cost (in \$) represents the present worth of all the costs, including the initial vehicle cost, maintenance costs, replacement costs, and energy costs. The levelized life-cycle costs (in \$/km) are based on an assumed vehicle life of ten years.

Table 1. Assumptions of Vehicle Characteristics

Parameter	Value
Vehicle Maximum Payload (kg)	4840
Vehicle Average Payload (kg)	2420
Rolling Resistance Coefficient	0.009
Aerodynamic Drag, $C_d A$ (m ²)	2.61
Drivetrain Efficiency (%)	85
Motor/Electronics Efficiency (%)	90
Generator/Electronics Efficiency (%)	90
Overall Regenerative	
Braking Efficiency (%)	40
Vehicle Life (yr)	10

Table 2. Assumptions of Engine Characteristics

Parameter	Value
Minimum bsfc (gm/kWh)	206
Fuel for Recharging Batteries (gm/kWs)	0.06
Idling Fuel Consumption (gm/s)	0.8 (for diesel bus) 0.3 (for hybrid bus)
Engine Cost (\$/kW)	80

Table 3. Assumptions of Battery Characteristics

Parameter	Value
Battery Specific Power @ 80% DOD (W/kg)	150
Battery Specific Energy @ C/3 (Wh/kg)	80
Battery Life @ 80% DOD (cycle)	600
Battery Shelf Life (yr)	5
Battery Efficiency (%)	75
Battery Charger Efficiency (%)	90
Battery Cost (\$/kWh)	150

Table 4. Economic Assumptions

Parameter	Value
Annual Cost Escalation (%)	0
Annual Discount Rate (%)	5
Diesel Fuel Cost (\$/gal)	0.6
Electricity Cost (\$/kWh)	0.05

Table 5. Driving Cycle Assumptions

Parameter	Value
Maximum Speed (km)	48
Average Speed (km)	20
Cycle Duration (s)	80
Daily Range (km)	260

The engine and battery characteristics of the hybrid configurations shown in the table represent the cost-optimized combinations for the specified mission. A diesel engine of about 106 hp is required for all of the hybrid configurations (compared with 285 hp for the diesel bus).

Unlike hybrid passenger cars, in which a large portion of the energy comes from electricity, electrical energy contributes only a small portion (usually less than 10%) to the total energy requirement of the heavy hybrid bus studied. Most of the energy must be provided by the on-board diesel engine. This limitation is based on life-cycle cost considerations. Other factors (such as space availability for battery pack), which were not considered in this paper, might also impose such a limitation.

SUMMARY AND DISCUSSION

A hybrid bus using a diesel engine in conjunction with a battery that meets the USABC's mid-term goals has been analyzed over an idealized bus-driving schedule in Chicago. Three hybrid configurations, two parallel and one series, were examined. The results indicate that fuel economy for the hybrid configurations, taking into account the regenerative braking, are comparable with that of the conventional diesel bus. Life-cycle costs are slightly higher because of the added weight and cost of the battery.

No evaluation of vehicle emissions was done in the present study. However, some qualitative statements regarding the emissions of the hybrid bus can be made. First, the small diesel engine in the hybrid bus will operate most of the time at a relatively constant speed, near its maximum power, which was known to result in greatly reduced exhaust emissions for a given total energy requirement. Also, because of its small size, the diesel engine in the hybrid bus is expected to experience much less severe transients than those in conventional diesel buses. Second, in the case of the series hybrid, the electrical energy to heat the catalyst is readily available from the battery, and the start of the engine can be delayed until the catalyst is warm without affecting vehicle driveability [4]. Hence, it can be expected that the emissions, especially the CO and HC emissions, from the series hybrid will be much lower than those from the conventional diesel bus.

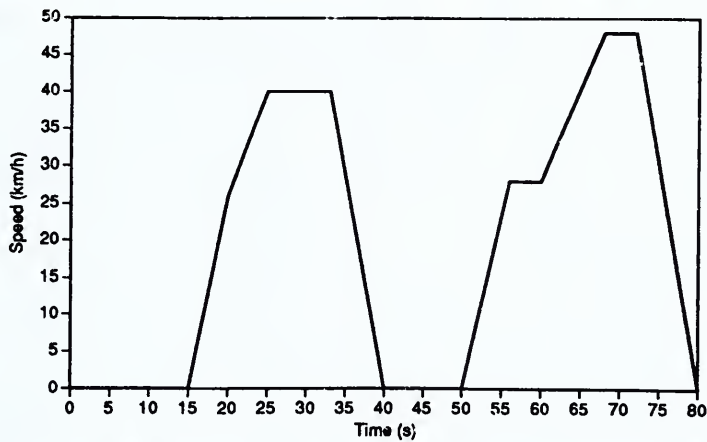


Fig. 2 An Idealized Chicago City Bus Driving Cycle

ACKNOWLEDGMENT

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Table 6. Hybrid Bus Technology Summary Comparison

Bus Type	Configuration	Engine Size		Battery Size		Battery Weight (kg)	Gross Vehicle Weight (kg)	Battery DOD (%)	Battery Life (yr)	Battery Cost (\$)	ICE Cost (\$)	Vehicle Cost (\$)	Annual Diesel Fuel (gal)	Annual Electricity (kWh)	Annual Energy Cost (\$)	Life-Cycle Cost	
		kW	hp	kW	kWh											\$	\$/km
Diesel	-	213	285	-	-	-	16169	-	-	-	17002	185739	14026	-	8416	348342	0.48
Hybrid	A	79	106	152	52	1037	17279	70	2	7746	6324	194630	12873	12746	8361	388589	0.53
Hybrid	B	79	106	152	52	1037	17279	70	2	7746	6324	194630	14674	12746	9442	395934	0.54
Hybrid	C	79	106	152	52	1037	17100	70	2	7746	6324	175490	4806	12746	9521	378402	0.52

